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Optimized Energy Management of a Single-House Residential Micro-Grid With Automated Demand Response

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Abstract— In this paper, an intelligent multi-objective energy management system (MOEMS) is proposed for applications in residential LVAC micro-grids where households are equipped with smart appliances, such as washing machine, dishwasher, tumble dryer and electric heating and they have the capability to take part in demand response (DR) programs. The superior performance and efficiency of the proposed system is studied through several scenarios and case studies and validated in comparison with the conventional models. The simulation results demonstrate that the proposed MOEMS has the capability to reduce residential energy use and improve the user's satisfaction degree by optimal management of demand/generation sides.

Index Terms-- Dispersed generation, residential AC micro-grid, energy management, master-slave control.

I. INTRODUCTION

The current electric grids were conceived many years ago when the needs of electricity were simple and small and the power generations were localized and built around communities. Such grids were designed for the utilities to provide electricity for the end users and then bill them once a month. This limited unidirectional interaction creates a hard situation for the grid to meet to the ever-changing and rising energy demands of the 21st century. On the other hand, by the emergence of the smart grids, two-way communications can be introduced between the utility and customers while electricity and information can be exchanged easily. In this environment, not only the grid can be operated more efficient, reliable, secure and greener, but also newer technologies such as wind and solar energy production can be enabled to be integrated [1]. With active participations of end users as informed consumers and better communications between them and the utilities, the smart grid will also replace the aging infrastructure of today's grid and manage the user's electricity need. More importantly, through utilization of a

communications means such as a home area network (HAN) it is possible to connect different smart devices and measurement units to an energy management system (EMS) and manage the operation of domestic devices in a cost effective way [2]. With a focus on residential EMSs, a large number of research and demonstration projects have been done recently and related findings have been published in different scientific papers [3]-[8]. As an example, authors of [3] have proposed a residential energy system for grid support applications to manage different distributed energy resources (DERs) considering minimum operation cost. Likewise, a single-objective energy management algorithm for domestic load scheduling has been outlined in [4] with regard to minimum electricity consumption cost. Authors of [5] have developed the same task scheduling and domestic energy management for a residential building taking into account different technical and operational issues. Other authors have also investigated such problem in multiple ways considering a time-domain simulation with dynamic thermo-electrical constraints [6], price-elastic load shifting [7] and incentive-based demand response (DR) actions [8]. As can be observed from the related literature, there is a large and growing body of research addressing the energy management problem within smart residential micro-grids considering different objectives and related constraints. Although this literature covers the extent of the problem of energy scheduling in future smart grids, there exist several challenges with smart management of energy-related production and consumption units. Thus, in this paper we propose a multi-objective dispatching model of a residential smart EMS (MOEMS) taking into account different DERs and smart household devices. To this end, first mathematical models of the mentioned system components together with the master-slave control of distributed generation units (DGs) are presented. Then the optimization model is introduced with regard to a

meaningful balance between saving energy and living comfortably. Finally, the control strategies with demand side participation under different operating conditions will be set up and tested.

II. SYSTEM CONFIGURATION AND MATHEMATICAL MODELLING

A block diagram of the proposed LVAC grid-connected residential micro-grid is shown in Fig. 1.

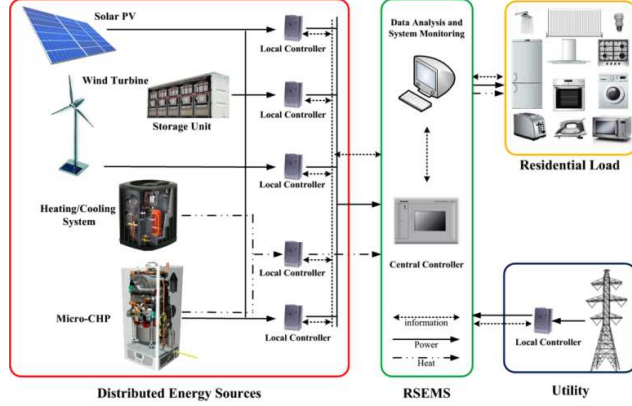


Fig. 1. Block diagram of a typical residential smart micro-grid. Within the mentioned system, both DG units and DR actions are operated in a way to enhance the system's efficiency and meet the user's requirements. In the mentioned structure, MOEMS plays the major role and manages the operation of domestic energy-related production and consumption units optimally with regard to different objectives and related constraints. As can be seen in the same figure, renewable energy sources such as photovoltaic (PV) and wind turbine (WT) are utilized as uncontrollable primary power sources of the system while the macro-grid (or utility) is used as an uninterruptible power supply that guarantees the system stability. In other word, since the micro-grid operates in a grid-connected mode, the utility has the capability to maintain AC bus voltage and frequency at their nominal values and other controllable DG units regulate their output powers according to the load level and power references coming from the MOEMS. Such controlling scheme known as master-slave is depicted in Fig. 2 and the related algorithm is shown in Fig. 3. Since optimal energy management of the aforementioned micro-grid can be regarded as a decision-making problem with multiple objectives and system constraints, the mathematical modeling of such problem can be presented as follows:

A. Distributed Energy Sources

1) Renewable Energy Sources (RESs)

RESs such as solar energy and wind can be used extensively in micro-grids as a clean and economic way of energy generation. The generated power of a WT can be expressed as:

$$P_{WT} = C_p(\lambda, \beta) \cdot \left(\frac{\rho \cdot A}{2} \right) \cdot V^3 \quad (1)$$

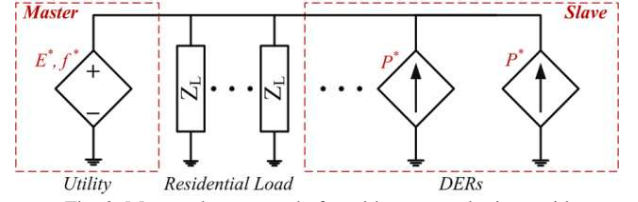


Fig. 2. Master-slave control of a grid-connected micro-grid

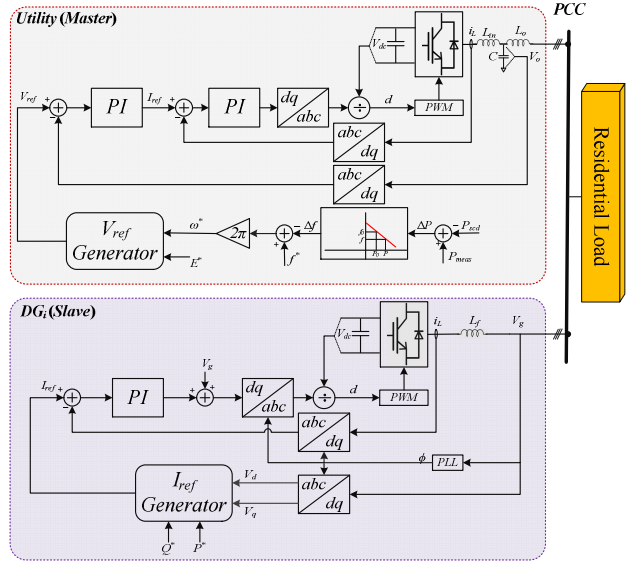


Fig. 3. Control algorithm of DG units

where ρ is the air density, C_p is the efficiency coefficient of the wind turbine, A is the rotor swept area (as shown in Fig. 4), V is the wind velocity and finally λ and β denote the tip speed ratio and pitch angle, respectively. Similarly, in a PV system, the following equation could be used to calculate the output power:

$$P_{PV} = Y_{PV} f_{PV} (G_T / G_{T,STC}) \left[1 + \alpha_p (T_c - T_{c,STC}) \right] \quad (2)$$

where, Y_{PV} is the rated capacity of the PV array, f_{PV} is the PV derating factor, G_T is the solar radiation incident on the PV array at any moment, $G_{T,STC}$ is the incident radiation at standard test conditions, α_p is the temperature coefficient of power, T_c is the PV cell temperature at any moment, and $T_{c,STC}$ is the PV cell temperature under standard test conditions.

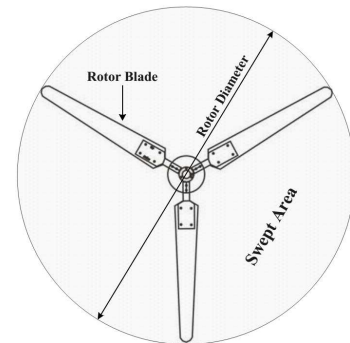


Fig. 4. Wind turbine swept area

2) Micro-Combined Heat and Power System

As shown in Fig. 5, a co-generation system generally consists of three units including a prime mover, an auxiliary boiler and a thermal storage tank and generates heat and electricity according to the following equations:

$$P_{CHP}^e(h) = g_{CHP}(h)\eta_e = P_{CHP}^{th}(h)(\eta_e / \eta_{th}) \quad (3)$$

$$P_{CHP}^e(h) \in [\underline{P}^e, \bar{P}^e] ; P_{CHP}^{th}(h) \in [\underline{P}^{th}, \bar{P}^{th}] \quad (4)$$

where, g_{CHP} represents the total fuel flow into the prime mover and \bar{P}^e (P^e) and \bar{P}^{th} (P^{th}) are the lower and upper limits on the CHP electrical (thermal) output, respectively. It should be noted that the same thermal equation and constraints must be met for an auxiliary boiler.

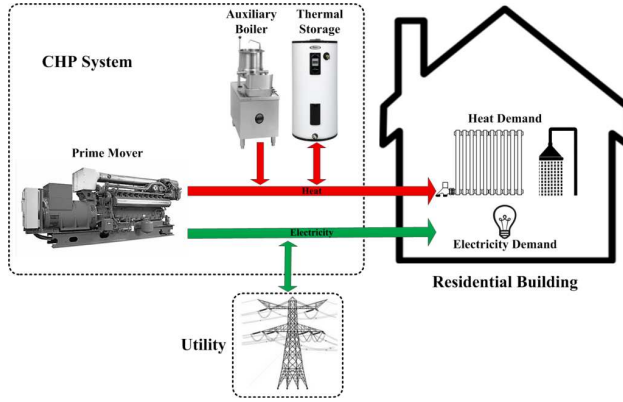


Fig. 5. Combined heat and power generation system

Considering the energy equivalent of the hot water inside the tank, the water storage temperature at each time can be also stated as follow:

$$T_{st}(h+1) = \frac{HWD(h) \cdot (T_{cw} - T_{st}(h)) + V_{tot} \cdot T_{st}(h)}{V_{tot}} + \frac{P_{CHP}^{th}(h) + P_{aux}^{th}(h)}{V_{tot} \cdot C_w} \quad (5)$$

$$T_{st}(h) \in [\underline{T}_{st}, \bar{T}_{st}] \quad (6)$$

3) Battery Energy Storage System (BESS)

Basically, the behavior of a BESS can be described mathematically through the following energy update function:

$$SOC(h+1) = SOC(h) + \frac{(P_{BESS}^{ch}(h) - P_{BESS}^{dch}(h)) \cdot \Delta h_{setp}}{E_{BESS}} \quad (7)$$

$$SOC(h) \in [SOC, \bar{SOC}] \quad (8)$$

where, $SOC(h)$ is the battery state of charge at hour h bounded by certain limits, and E_{BESS} is the battery capacity in kWh . Likewise, P_{BESS}^{ch} and P_{BESS}^{dch} are the charging and discharging power of the battery.

B. Thermal Model of a Residential House

For efficient performance of a MOEMS, it is necessary to understand the heat dynamics of a residential building with regard to different internal/external heat sources and sinks. Generally, the internal heat gain of a building is estimated according to the heat generated by

the occupants, lights and appliances such as stove, television, radio, etc. Heat could also be added to the space mainly due to the presence of heating system and the effect of solar radiation. Regarding a radiant floor heating/cooling system (RFH/CS), the amount of heat that is supplied to the floor at each time step is calculated as follows:

$$Q_{RH}(h) = (u_{RH}(h)\eta_H(h) - (1 - u_{RH}(h))\eta_C(h))P_{RH}(h) \quad (9)$$

$$P_{RH} \in [0, \bar{P}_{RH}] ; \eta_H \in [\underline{\eta}_H, \bar{\eta}_H] ; \eta_C \in [\underline{\eta}_C, \bar{\eta}_C] \quad (10)$$

where, u_{RH} is a binary variable showing the operating mode of the RFH/CS ("1": heating, "0": cooling), and $P_{RH}(h)$ is the power consumption of the heat pump at hour h ; η_H (η_C) is the heating (cooling) performance coefficient for the above mentioned system.

Likewise, the Sun plays a great role on the actual heating/cooling load of a building by its direct and diffuse radiation. The amount of heat obtained directly from solar radiation (I) when it enters through the glazing and is absorbed by the floor area (A_f) with solar absorptivity of α_f could be computed as following:

$$Q_{sf}(h) = \alpha_f A_f I(h) \quad (11)$$

Similarly, at each time step, the heat flows into an exterior surface of a building subjected to solar radiation, and contributes to the heat gain of the building as follows:

$$Q_{si}(h) = U A_s \left\{ \left(T_{out}(h) + \frac{\alpha_s I(h)}{h_o} - \frac{\varepsilon \sigma (T_{out}^4(h) - T_{surr}^4(h))}{h_o} \right) - T_{in}(h) \right\} \quad (12)$$

where, σ is Stefan-Boltzmann constant, h_o is the combined convection and radiation heat transfer coefficient and α_s , ε , U are the solar absorptivity, emissivity, and the overall heat transfer coefficient of the exposed surface with the area of A_s , respectively. In a similar manner, T_{in} , T_{out} , and T_{surr} are the indoor, outdoor and the average surrounding surface temperatures.

Considering the mentioned heat flows, the thermal behavior of a house in terms of temperature update functions could be determined as follows:

$$T_{in}(h) = T_{in}(h-1) + \Delta h_{step} \left(\frac{Q_{fi}(h) + Q_{si}(h) - Q_{io}(h)}{m_i c_{p,i}} \right) \quad (13)$$

$$T_f(h) = T_f(h-1) + \Delta h_{step} \left(\frac{Q_{RH}(h) - Q_{fi}(h)}{m_f c_{p,f}} \right) \quad (14)$$

where, Q_{io} is the heat flow between the indoor air node and the outdoor environment, Q_{fi} is the heat flow between the floor and the indoor, and m_f (m_i) and $c_{p,f}$ ($c_{p,i}$) are the mass and specific heat capacity coefficients of the floor (indoor air), respectively.

C. Automated Demand Response and Load Scheduling

Automated DR programs can be a more cost-effective alternative than adding generation capabilities to meet the peak and or occasional demand spikes. The objective of DR is to actively engage customers in modifying their consumption in response to pricing signals. This objective

could be met through wise management of controllable loads such as washing machine, tumble dryer, dishwasher, etc. Each schedulable load (here named as task) has its own list of operating parameters (LOP) that need to be set by residents for efficient scheduling as:

$$TLOP_i = \left\{ \underbrace{Start\ Time, End\ Time}_{h_{st,i}, h_{et,i}}, \underbrace{Runtime}_{RT_i}, \underbrace{Power}_{P_{s,i}}, \underbrace{Desired\ Operating\ Interval}_{DOI_i}, \underbrace{Priority}_{ID_i} \right\} \quad (15)$$

Moreover, for such tasks several constraints must be met correspondingly. First, each task must be completed within its valid start-end time period $T_{v,i}=[h_{st,i}, h_{et,i}]$. Second, some tasks cannot be cancelled or set to standby once they are started. Third, operation of one task (e.g., task j) may depend on the completion of another task (e.g., task i). Finally, parallel operation of tasks at each time step should be limited to a certain level named as the upper power consumption of a house (\bar{P}_D).

D. Objective Function

In this work, the following mixed objective function is considered as the model of optimization:

$$\begin{aligned} Min : J = & \zeta_1 \sum_{h \in T} \left(\rho_{grid}(h) \cdot P_{grid}(h) + \rho_{gas} \cdot (u_{CHP}(h) \cdot g_{CHP}(h) \right. \\ & \left. + u_{aux}(h) \cdot g_{aux}(h)) \right) \\ & + \zeta_2 \sum_{h \in T} \sum_{i \in N} (ID_i DSL_i(h)) \end{aligned} \quad (16)$$

where, $P_{grid}(h)$ is the amount of power exchanged with utility at hour h , ρ_{gas} and ρ_{grid} are the natural gas and real-time electricity prices, respectively. $g_{aux}(h)$ is the total amount of gas consumed by the auxiliary boiler at hour h and u_{CHP} and u_{aux} are the on/off states of the corresponding units. Likewise, $DSL_i(h)$ is the user's dissatisfaction level when task i is executed at hour h as shown in Fig. 6.

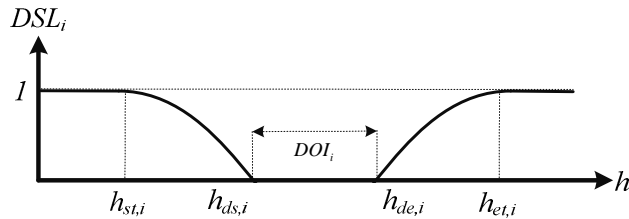


Fig. 6. Definition of user's dissatisfaction degree

III. SIMULATION STUDY

In this section, performance analysis of our proposed model for optimal energy management in a residential smart micro-grid is presented through different computer simulations. The case study is one of the variations of a real single-zone, low-energy house in Sydney, Australia, whose constructional elements are adopted from [9]. For this case study, different types of DG units as well as schedulable tasks are introduced using the parameters shown in Tables I-II. The power stage and control system parameters are also tabulated in Table III. In the performed simulation studies, the hourly outdoor temperatures in hot and cold weather conditions, wind

speed, solar radiation and real time electricity prices were considered as the 24-hour profiles depicted in Fig. 7.

TABLE I
OPERATING PARAMETERS FOR DG UNITS AND SCHEDULABLE TASKS

Parameter	Value	Unit	Parameter	Value	Unit
Renewable Energy Sources					
ρ	1.18	Kg/m^3	A	120	m^2
D_{rotor}	12.35	m	a_p	-0.44	$\%/^{\circ}C$
Y_{PV}	0.25	kW	f_{PV}	77	$\%$
$G_{T,STC}$	1	kW/m^2	$T_{c,STC}$	25	$^{\circ}C$
Micro-Combined Heat and Power System					
$\underline{P}^e, \bar{P}^e$	0.3, 1.5	kW	$\underline{P}_{aux}^h, \bar{P}_{aux}^h$	4, 19	kW
g_{CHP}	92.4×10^{-3}	m^3/h	$\eta_e, \eta_{th}, \eta_{aux}$	30, 70, 86	$\%$
$\underline{T}_{st}, \bar{T}_{st}$	60, 80	$^{\circ}C$	T_{cw}	10	$^{\circ}C$
Battery Energy Storage System					
E_{BESS}	24	kWh	SOC, \bar{SOC}	20 - 80	$\%$
$\bar{P}_{ch}, \bar{P}_{dch}$	3.3, 3.3	kW	η_{ch}, η_{dch}	87, 90	$\%$
Radiant Floor Heating/Cooling System					
\bar{P}_{RH}	2	kW	T_{set}	25	$^{\circ}C$
$\underline{\eta}_H, \bar{\eta}_H$	100, 400	$\%$	$\underline{\eta}_C, \bar{\eta}_C$	100, 300	$\%$

TABLE II
SCHEDULABLE TASKS PARAMETERS

Appliance	T_v	DOI	RT	P_s	ID
Washing Machine	07-21	08-14	2	0.5	1
Dishwasher	06-18	14-18	2	0.7	2
Tumble Dryer	09-21	11-17	1	1.8	1
Microwave	08-19	11-14	1	0.9	3
Electric Kettle	04-12	06-07	1	1.0	3

TABLE III
POWER STAGE AND CONTROL PARAMETERS

Parameters	Symbol	Value	Unit
Power Stage			
Nominal bus voltage	V^*	230	V
Nominal bus frequency	f^*	50	Hz
Filter capacitance	C	2200	μF
Filter inductance of master unit	L_{in}	1.8	mH
Filter inductance of slave units	L_f	3.6	mH
Output inductance	L_o	0.1	mH
Control System Parameters			
Voltage Loop PI	k_{pV}, k_{iV}	0.1, 200	$-, s^{-1}$
Current Loop PI	k_{pI}, k_{iI}	15, 50	$-, s^{-1}$
Frequency Droop	m_d	0.003	$rad \cdot s^{-1} / W$

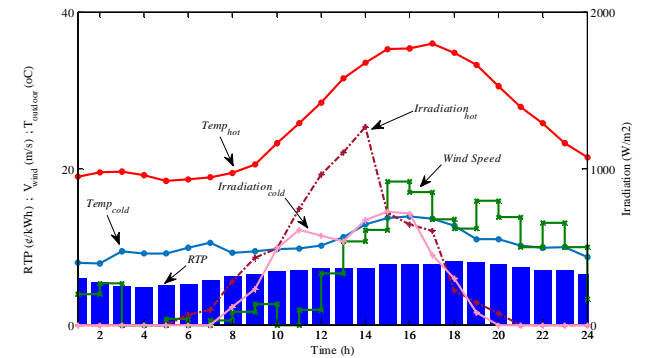


Fig. 7. Environmental information profiles for the proposed problem

Fig. 8 shows the performance of the proposed MOEMS compared to a conventional one through

different operating conditions. It should be mentioned that the conventional EMS (CEMS) gets real-time price signal and determines the tasks scheduling in a cost effective way under RTP changes; however user's preference is not considered as an objective. It also tries to maintain the house within the comfortable temperature ranges.

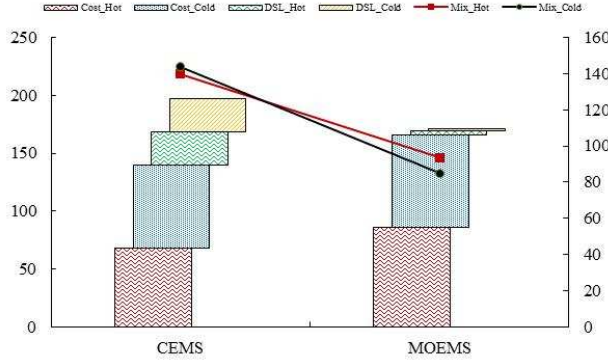


Fig. 8. Performance comparison between MOEMS and CEMS

As can be observed from the simulation results, although the CEMS gets the RTP signal and determines the tasks scheduling in a cost effective way, the mixed objective function that includes the user's preferences and satisfaction level gets a worse value with the proposed MOEMS. On the other hand, the proposed structure benefits from an advanced EMS and could manage both demand and supply sides in a way to reduce domestic energy usage and ensure optimal task scheduling for the inhabitants. Based on the simulations results, the MOEMS has improved the mixed objective function value up to 33% and 40% with respect to the CEMS in hot and cold weather conditions, respectively.

Regarding a cold weather condition, the optimal management of the controllable appliances and DG units together with the amount of power exchange between the house and the utility for a given demand profile has been also demonstrated in Fig. 9. As it can be observed from Fig. 9, MOEMS tracks the electricity usage by the hour and finds the most efficient solution to supply the demand and/or shift (load) activities into time-frames when the electricity price is less expensive while considering user's comfort level. In a similar manner, most of the residential demand is supplied by the utility during some periods of time when the RTP is relatively low and the charging process of the BESS is carried out with less cost. On the other hand, with the rise of RTP and the need for more electricity during the other hours of the day, MOEMS dispatches controllable DG units in a way not only to meet the load, but also to sell the surplus of energy to the utility and make profits. It is also worthy to note that in the mentioned residential grid-connected micro-grid, the utility plays the role of master unit and tries to maintain the frequency constant and regulate the voltage at PCC using current and voltage controllers. Likewise, other controllable DGs behave as slave units and regulate their output powers by the use of an inner-loop PI current controller according to the references signals coming from the MOEMS. At the same time, the optimal

scheduling of the household appliances is done effectively taking into account the operational constraints and users' preferences.

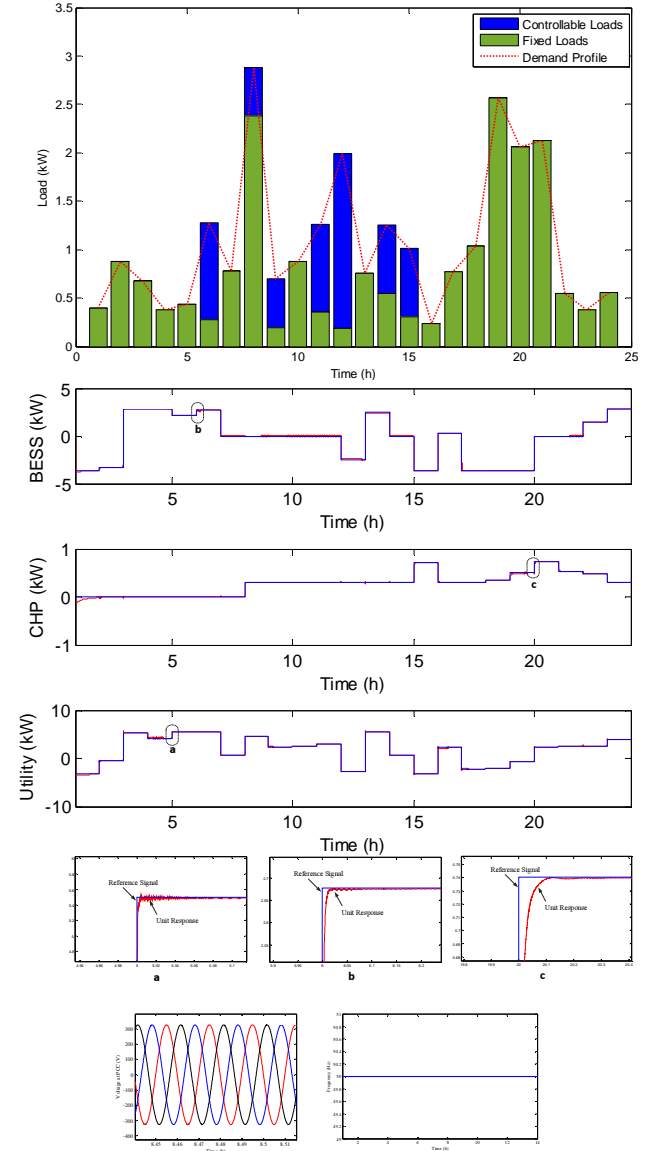


Fig. 9. Optimal operation of controllable household appliances and DG units using MOEMS

Fig. 10 illustrates the thermal behavior of the building in different weather conditions. As it can be seen, heat can be transferred between the indoor air node and outdoor environment based on the temperature differences at the mentioned nodes, which in turn affects the heating/cooling load of the building. In a given hot summer day, the house not only captures the heat from the Sun directly, but also absorbs the solar radiation in the walls and the roof and emits that heat later in the day. Regarding this point, the RFH/CS must work more to remove extra heat from the indoor environment. On the contrary, the RFH/CS must be operated in the heating mode in a cold winter day to keep the indoor temperature within the comfort range, although the internal and external heat gains of the building assist the heating process.

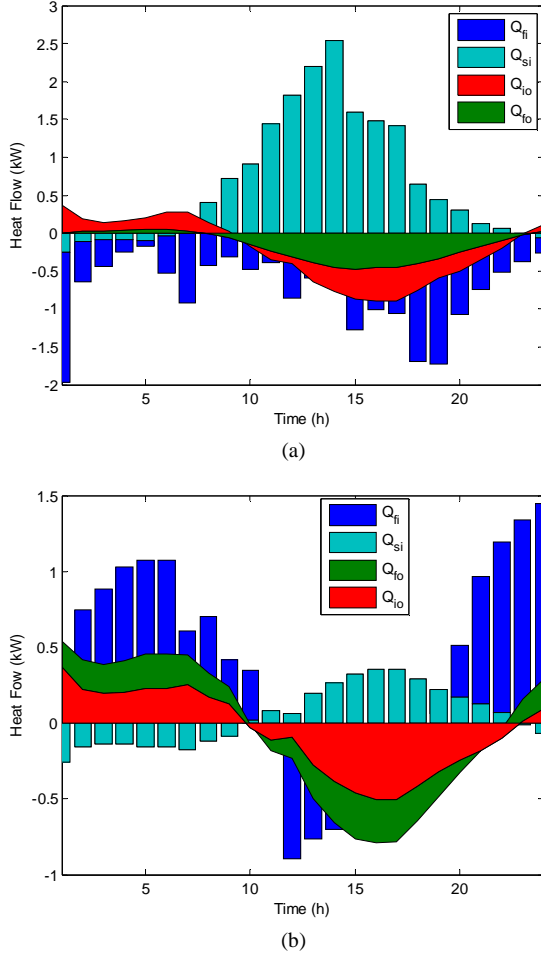


Fig. 10. Different heat flows based on the thermal model of the residential building: a) summer, b) winter

IV. CONCLUSION AND FUTURE WORK

In this paper, an intelligent multi-objective energy management system for applications in LVAC micro-grid was described and validated via different operating conditions. The proposed framework covered different key modeling aspects such as master-slave control of DG units and thermal dynamics of a residential building where households were supposed to be equipped with smart appliances and had the capability to take part in demand response programs. Moreover, different distributed heat and electricity generators such as radiant-floor heating/cooling system, renewable energy sources, battery and micro-CHP unit were integrated to provide energy saving and a comfortable lifestyle for residents. It was demonstrated that the proposed energy management system has the capability to reduce domestic energy usage and improve the user's satisfaction degree through management of loads and generations within the smart micro-grid.

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